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Comparison of Global Warming Impacts of Automobile Air-Conditioning Concepts

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The global warming impacts of conventional vapor compression automobile air conditioning using HFC-134a are compared with the potential impacts of four alternative concepts. Comparisons are made on the basis of total equivalent warming impact (TEWI) which accounts for the effects of refrigerant emissions, energy use to provide comfort cooling, and fuel consumed to transport the weight of the air conditioning system. Under the most favorable assumptions on efficiency and weight, transcritical compression using CO_2 as the refrigerant and adsorption cooling with water and zeolite beds could reduce TEWI by up to 18% relative to HFC-134a compression air conditioning. Other assumptions on weight and efficiency lead to significant increases in TEWI relative to HFC-134a, and it is impossible to determine which set of assumptions is valid from existing data. Neither Stirling cycle or thermoelectric cooling will reduce TEWI relative to HFC-134a. Brief comments are also made concerning technical barriers that must be overcome for successful development of the new technologies.

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Introduction

Concern over the adverse environmental impacts of chlorofluorocarbons released into the atmosphere led to the Montreal Protocol and its various amendments phasing out the manufacture and use of CFCs and HCFCs. The scheduled phase-out in turn led to evolutionary changes in designs of equipment and manufacturing processes to use CFC substitutes such as hydrofluorocarbons (HFCs) and hydrocarbons as refrigerants, foam blowing agents, and solvents. Now concerns are being raised about the greenhouse effect and the effects that these chemicals may have on global warming. Is one family of compounds being replaced by another that also has adverse, possibly worse, environmental effects? Would society in fact be better served by a quantum step to completely different technologies which don't depend on chemicals that may have unknown, adverse impacts on the environment?

This paper examines five technologies that could conceivably be used to provide automobile air conditioning; conventional Rankine cycle vapor compression air conditioning using HFC-134a, a compression cycle using CO_2 as the refrigerant, Stirling cycle refrigeration, adsorption cooling, and thermoelectric cooling. Only one of these, compression with HFC-134a, has been proven to be technically and commercially viable, while the other four technologies are in various stages of development; some of them exist only on paper and while others have been demonstrated in laboratory prototypes. The discussion in this paper focuses very narrowly on a comparison of the global warming impacts of each of these five technologies; it does not address the many barriers which must be overcome before any of the four new technologies could be commercialized. Some of these obstacles are very significant and could make the alternatives economically or technically infeasible.

The global warming impacts are evaluated including both the direct effects of refrigerants released into the atmosphere and also the indirect effects of CO_2 emissions. The carbon dioxide is significant in that CO_2 is generated from burning fuel simply to transport the weight of the air-conditioning system as well as to provide the energy to drive the compressors, the electricity for the fans, blowers, or thermoelectric cells, and to regenerate adsorption beds. The alternative air-conditioning technologies are compared using the concept of total equivalent warming impact (TEWI).

Several fundamental factors are used in this paper to convert from estimated gasoline use to resulting emissions of CO_2:

- an engine efficiency of 25%,
- 2.32 kg CO_2 / liter gasoline consumed,
- 0.243 kg CO_2 / kWh fuel input, and
- 57 liters of gasoline / 100 kg incremental vehicle weight / 10,000 km (10 gal./100 lb/10,000 miles) (Halberstadt 1991).

Conventional Vapor Compression A/C

Several assumptions are necessary to establish a basis for comparing different concepts for vehicle air-conditioning. Those chosen for this discussion are fairly representative of a typical family passenger car in the United States (Fischer 1994):

- 7.0 kW cooling capacity (24,000 Btu/h), 107 a/c operating hours per year,
- 13.6 kg (30 lbs) weight of a/c equipment (compressor and transmission, condenser, evaporator, belts, hoses, etc.)
- 16,400 km/y (10,200 m/y) vehicle use,
- 11 year useful lifetime for the a/c system.

The power requirements of the air-conditioning system can then be estimated by Eq. 1:

$$P_{input} = \frac{7.0 \text{ kW output}}{COP} \times \frac{1}{\eta_{engine}} \times h \qquad (1)$$

where η_{engine} is the engine efficiency and "h" is the annual operating hours for the air conditioner.

Historically, the coefficient of performance, COP, for this application is computed for CFC-12 at a condensing temperature of 65.6°C (150°F) and evaporating at 4.4°C (40°F) with 11°C (20°F) subcooling and 0°C (0°F) superheat. This condensing temperature results in a higher high-side pressure for the HFC-134a than was experienced with CFC-12, and manufacturers made modifications have in condenser designs to achieving the same pressures as CFC-12 systems. These changes resulted in lower the condensing temperature to 60°C (140°F) (for future reference the high side pressure is 16.9 bar (1700 kPa, 245 psia)). Assuming a typical compressor efficiency of 61% and 15% losses for belts, transmission, and evaporator fan results in a COP of 2.04 for HFC-134a. The power input for air conditioning is thus 1470 kWh per year with CO_2 emissions of 355 kg per year; 3900 kg CO_2 for the 11 year lifetime.

Gasoline use for transporting the weight of the air conditioner can be estimated using Eq. 2:

$$F = m_{a/c} \times \frac{57 \text{ liters gasoline / 100 kg}}{10{,}000 \text{ km}} \times d \qquad (2)$$

where $m_{a/c}$ is the mass of the air-conditioning system and "d" is the annual driving distance. Using the 13.6 kg weight of the air conditioner and 16,400 km/y assumptions above this results in an estimate of 12.7 liters of gasoline per year or 29.5 kg CO_2 per year for transporting the system; 325 kg CO_2 for the 11 year lifetime.

Finally, there is a direct effect from releases of refrigerant from accidents, servicing, permeation through hoses, and losses around the compressor seals as well as refrigerant left in the system when it is retired. Historical data on refrigerant losses should not be used in estimating the effects of these emissions because of significant changes in service and refrigerant recovery practices and efforts to manufacture tighter systems, but accurate current estimates are not available. In light of this uncertainty, high and low loss estimates of 55 to 110 g/year of HFC-134a are used and that all but 55 g of the refrigerant are recovered when the system is retired (95% of the 1100 g charge is recovered). The direct effect can then be computed from Eq. 3:

$$\text{Direct Effect} = \left[\dot{m}_{losses} \times L_{years} + m_{retire}\right] \times GWP \qquad (3)$$

The direct effect for the HFC-134a air conditioner is then 860 to 1640 kg CO_2 (using a 100 year integration time horizon, $GWP_{134a} = 1300$).

The total equivalent warming impact, or TEWI, of the conventional HFC-134a air conditioner is thus 5100 to 5900 kg CO_2.

Transcritical CO_2 Air Conditioner

One possible technology that has been proposed as an alternative to the conventional compression system is an air conditioner that uses CO_2 as the refrigerant and operates above the critical point. The obvious advantage of this concept from a global warming perspective is that the direct effect of the refrigerant is negligible compared to halocarbon systems (e.g. GWP=1 compared to GWP=1300). Much of the research and testing of this technology for automobile air conditioning has been done in Norway (Lorentzen 1993, Pettersen 1993, Pettersen 1994) with some proprietary testing in the United States.

This system is similar to conventional vapor compression air conditioners in that it would use a belt driven compressor with a clutch for on/off cycling, high and low side heat exchangers, and an expansion valve. The high-side heat exchanger operates above the critical point of the refrigerant, so vapor condensation does not occur during heat transfer.

Two major uncertainties exist concerning the construction and operation of a transcritical CO_2 automobile air conditioner: the efficiency and the weight of a production line system. Pettersen (1993a) published COP data for a range of ambient air temperatures which indicate a favorable comparison with a CFC-12 air conditioner. These data have been combined using assumptions on idling and highway driving to give a weighted COP of 1.94 (Fischer 1994). This value, however, is inconsistent with the theoretical estimate of COP derived for HFC-134a; calculations using a condensing pressure consistent with a sink temperature of 65.6 °C (150°F) with the evaporating and suction gas temperatures used in the fluorocarbon calculations result in a COP of only 1.28 (similar compressor efficiency and drive- losses). The high-side pressure of a CO_2 air conditioner is approximately 110 bar (11,000 kPa, 1600 psia); this is an extremely high pressure (compare with 17 bar for HFC-134a). The difference in COPs is significant and needs to be resolved through further testing; CO_2 emissions and TEWI are calculated using both values.

System testing in Norway used a laboratory prototype constructed for proof-of-concept testing without regard to system size and weight. This prototype weighed 42 kg (90 lbs), although projections estimate that a production line model could be made weighing in the neighborhood of 12 kg (26 lbs) (Pettersen 1994). Both the high and low weight estimates are used in calculating fuel requirements for transporting the air conditioner and TEWI.

Applying these numbers for efficiency and weight into Eqs. 1 and 2 result in estimates of 4100 to 6300 kg CO_2 to power the air conditioner and 300 to 1000 kg to transport the system. The TEWI then would be between 4400 and 7300 kg CO_2.

Adsorption Air Conditioner

Research has also been done on using waste heat from the engine to provide cooling with zeolite adsorption beds with water as the refrigerant (Schwarz 1993). In an adsorption system the refrigerant is adsorbed into one zeolite bed at low pressure while a second zeolite bed is heated, using engine heat or heat from an auxiliary burner, rejecting refrigerant at high pressure. More than one pair of zeolite beds may be necessary to provide a fairly steady supply of cool air to the passenger compartment. The performance of adsorbent beds used in industrial processes are known to degrade in time; the long-term performance of a water/zeolite air conditioner is unknown and would need to be demonstrated before this technology could be commercialized.

Tests of a prototype system showed thermal COPs of 0.27 to 0.31 during the desorption, cooling process with an average COP of 0.29 (these efficiencies are primary energy values and not directly comparable to data provided for compression systems). The zeolite beds result in a large, heavy system with a published weight of 40 kg (90 lbs) for a 3.5 kW (12,000 Btu/h) prototype system; a 7.0 kW system would consequently weigh approximately 80 kg (180 lbs). The zeolite beds are much larger than the belt and clutch driven compressor they are replacing in a conventional air conditioner, but no consideration has been given in this discussion to the impact of the increased dimensions on vehicle design.

Equation 1 is inappropriate for computing adsorption energy use, since results have been reported in terms of primary energy use. Estimates of energy use are made using Eq. 4:

$$P_{input} = \frac{7.0 \text{ kW output}}{COP_{primary}} \times \left[1 - \eta_{waste\ heat}\right] \times h \tag{4}$$

where $1 - \eta_{waste\ heat}$ is the fraction of the time an auxiliary burner is required to regenerate the zeolite beds and "h" is once again the annual operating hours for the air conditioner (107 for the U.S.). Schwarz reported that waste heat should be able to regenerate the adsorber beds 60% of the time for the laboratory prototype, so that the auxiliary burner is required to provide 40% of the cooling (1993). Further development may be able to decrease the dependence on auxiliary power, so an optimistic assumption of only 30% of the energy input from the auxiliary burner is used. Additional calculations are presented for comparison assuming that only 40% of the energy input could be provided by waste heat. These assumptions result in estimates of 190 to 375 kg CO_2 per year from the auxiliary burner; assuming the same 11 year lifetime as the compression systems would result in an indirect effect of 2100 to 4100 kg CO_2. The thermal COP does not include energy required to power a 125 W evaporator blower; including this energy use adds an additional 200 kg CO_2 for the lifetime of the air-conditioning system.

The CO_2 emissions of 1900 kg resulting from transporting the water/zeolite air conditioner can be estimated using Eq. 2. The most optimistic assumptions thus give a TEWI of 4200 kg CO_2, while the less favorable assumptions a TEWI of 6200.

Stirling Cycle Air Conditioning

The Stirling refrigeration cycle uses helium or hydrogen as the refrigerant in a constant volume machine with a regenerator separating the hot and cold-side heat exchangers. The Stirling cycle is known to have high efficiencies at very low operating conditions, although this advantage decreases at less severe conditions and the efficiency is lower than Rankine cycle vapor compression at conditions corresponding to most consumer applications. A manufacturer of Stirling equipment reported estimated COPs of 1.3 to 1.7 at automobile air-conditioning temperatures (STM); this is only 65% to 85% of the COP for HFC-134a. These efficiencies are used in Eq. 1 with an estimated system weight of 32 kg (70 lbs) (STM) in Eq. 2 to compute a TEWI of 5500 to 6900 kg CO_2.

Thermoelectric Air Conditioning

Thermoelectric cooling based on the Peltier effect can be accomplished by passing an electrical current through a junction constructed with two dissimilar conductors or semiconductors. The cooling effect is proportional to the Seebeck coefficients of the two materials and the efficiency is represented in terms of the figure of merit, Z, for the two materials. The highest figure of merit obtained under laboratory conditions is 0.0035 (Mei 1994). The COP of the junction depends on Z and the hot and cold junction temperatures; Mei reported a COP of 0.42; TEWI are estimated using this COP and also a theoretically possible COP of 1.20 (major breakthrough in materials for the thermoelectric junction, tripling the figure of merit, would be necessary to reach this COP). A system weight of 22 kg (48 lbs) is estimated based on the weight of off the shelf components designed for much smaller systems (Fischer 1994). Substitution of these efficiencies and weight into Eqs. 1 and 2 results in estimates of TEWI 7200 to 19,000 kg CO_2.

Summary

TEWI have been estimated for a conventional compression air conditioner using HFC-134a and four alternative technologies using representative cooling requirements and operating conditions for the United States. Ranges of assumptions are used when there is significant uncertainty in weight, efficiency, or refrigerant emissions. The results show:

- 5100 to 5900 kg CO_2 for a 7.0 kW HFC-134a air conditioner with the low end of the range representing average refrigerant emissions of 55 g per year and the high end based on 110 g per year,
- 4400 to 7300 kg CO_2 for a comparable air conditioner using CO_2 as the refrigerant; the

low end is based on the most optimistic estimates of system COP and weight while the high end is based on a COP estimate consistent with the COP of a HFC-134a air conditioner and the weight of the laboratory prototype,

- 4200 to 6200 kg CO_2 for a water/zeolite adsorption air conditioner; the low end is based on waste heat providing 70% of the cooling energy input while the high end of the range corresponds to only 40% of the energy input coming from waste heat,

- 5500 to 6900 kg CO_2 for a Stirling cycle air conditioner; the range is based on the range of COPs reported by industry, and

- 7200 to 19,000 kg CO_2 for a thermoelectric air conditioner; the low end corresponds to a major breakthrough in materials research leading to a three-fold improvement in figure of merit, the high end is computed by using the best efficiency measured under laboratory conditions.

Conclusions

This discussion focused only on of the global warming impacts of each of these technologies and did not address the many technical and economic barriers which must be overcome before any of the new technologies could be commercialized; some of these obstacles are known to be significant. If they can be overcome, there may be a potential for the transcritical CO_2 compression system and the adsorption air conditioner to reduce TEWI for automobile air conditioning (both systems could also have higher TEWI than the conventional HFC-134a air conditioner). Laboratory prototypes have been constructed and tested for each of these technologies, although the water/zeolite adsorption system had only half of the cooling capacity necessary for vehicles in the United States. Uncertainties surrounding the system efficiency, weight, and use of engine waste heat need to be resolved before a definite statement can be made about how much TEWI may be reduced.

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